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***Abstract*. The National Ignition Facility (NIF), currently under construction at the Lawrence Livermore National Laboratory, is a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter diameter target chamber with room for nearly 100 experimental diagnostics. When completed, NIF will be the world's largest and most energetic laser experimental system, providing an international center to study inertial confinement fusion and the physics of matter at extreme energy densities and pressures. NIF's 192 energetic laser beams will compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions.**

Laser hardware is modularized into line replaceable units such as deformable mirrors, amplifiers, and multi-function sensor packages that are operated by the Integrated Computer Control System (ICCS). ICCS is a layered architecture of 300 front-end processors attached to nearly 60,000 control points and coordinated by supervisor subsystems in the main control room. The functional subsystems – beam control including automatic beam alignment and wavefront correction, laser pulse generation and pre-amplification, diagnostics, pulse power, and timing – implement automated shot control, archive data, and support the actions of fourteen operators at graphic consoles. Object-oriented software development uses a mixed language environment of Ada (for functional controls) and Java (for user interface and database backend). The ICCS distributed software framework uses CORBA to communicate between languages and processors. ICCS software is approximately 3/4 complete with over 750 thousand source lines of code having undergone off-line verification tests and deployed to the facility.

NIF has entered the first phases of its laser commissioning program. NIF has now demonstrated the highest energy 1ω, 2ω, and 3ω beamlines in the world. NIF's target experimental systems are also being installed in preparation for experiments to begin in late 2003. This talk will provide a detailed look at the status of the control system.

I. INTRODUCTION

The National Ignition Facility (NIF) under construction at the Lawrence Livermore National Laboratory (LLNL) will be a national center for the U.S. Department of Energy to study inertial confinement fusion and the physics of extreme energy densities and pressures. Construction of the building that houses the laser system was completed September 2001 and the construction of all 192 ultra-clean and precision aligned beam path enclosures was completed September 2003 (Figure 1). In late 2002 NIF began activating its first four laser beam lines. By July 2003 NIF had delivered world-record single beam laser energy performance in the primary, second and third harmonic wavelengths (NIF's primary wavelength is 1.06 micron infrared light). When completed in 2008, NIF will provide up to 192 energetic laser beams to compress deuterium-tritium fusion targets to conditions where they will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions [1,2].

Figure 1: The National Ignition Facility (NIF).

The Integrated Computer Control System (ICCS) for NIF is a layered architecture of 300 front-end processors (FEP) coordinated by supervisor subsystems including automatic beam alignment and wavefront control, laser and target diagnostics, pulse power, and shot control timed as required to 30ps. Software is based on an object-oriented framework using CORBA that incorporates services for archiving, machine configuration, graphical user interface, monitoring, event logging, scripting, alert management, and access control. Software coding in a mixed language environment of Ada95 and Java is 3/4 complete at over 750 thousand source lines. The control system is currently firing shots and conducting early target experiments using the first 4 beams.

II. DESCRIPTION OF NIF AND STATUS

NIF consists of a number of subsystems including amplifier power conditioning modules to drive large flashlamp arrays, the injection laser system consisting of the master oscillator and preamplifier modules, the main laser system along with its optical components, the switchyards that direct beams toward the target, and the 10-meter diameter target chamber and its experimental systems. The entire laser system, switchyards, and target area is housed in an environmentally controlled building. The integrated computer control system is operated from a central control room in the core of the facility to monitor, align, and operate the more than 60,000 control points required for NIF's operation.

NIF's laser system is comprised of 192 high-energy laser beams. For inertial fusion studies the laser beams will produce a nominal 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of laser energy in the third harmonic (3ω, or 351 nanometer wavelength) onto a target.

NIF has entered the first phases of its laser commissioning program and has successfully operated the first 4 beams. NIF has now demonstrated the highest energy 1ω, 2ω, and 3ω beamlines in the world. A detailed description of the NIF and overall project status is described in [3].

III. CONTROL SYSTEM

The Integrated Computer Control System (ICCS) is being developed to operate the NIF facility from a central control room with 14 operator positions (Figure 2). The operator consoles provide the human interface in the form of operator displays, data retrieval and processing, and coordination of control functions. Supervisory software is partitioned into several cohesive subsystems, each of which controls a primary NIF subsystem such as beam alignment or power conditioning. Several databases and file servers are incorporated to manage both experimental data and data used during operations and maintenance.

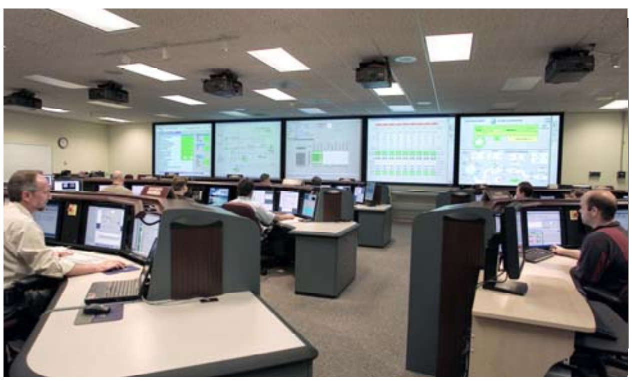

Figure 2: The NIF Control Room supports 14 operators.

Each operator position has a PC workstation with 3 flat panel displays running Java graphical user interfaces. Sun workstations were initially planned to run the thin-client Java GUIs, but it was determined that high-end PCs provided a more optimal solution for many subsystems. The Java code easily ports to either host operating system.

The principal software infrastructure is a custom framework based on CORBA distribution that provides central services and patterns for building a layered architecture of supervisors and front-end processors [4].

A. Architecture

The ICCS is a layered architecture consisting of front-end processors (FEP) coordinated by a supervisory system. Supervisory controls, which are hosted on UNIX workstations, provide centralized operator controls and status, data archiving, and integration services. FEP computers incorporate processors (VxWorks / PowerPC or Solaris / SPARC) that interface to over 45,000 control points attached to VME-bus or PCI-bus crates respectively. With the first 4 beams of NIF, at least one of every device and controller is installed and operating from the control room. Typical devices are stepping motors, transient digitizers, calorimeters, and photodiodes. FEP software provides the distributed services needed to operate the control points by the supervisory system. The software is distributed among the computers with plug-in extensibility for attaching control points and other software services by using CORBA.

Functions requiring real-time implementation are allocated to FEPs (or embedded controllers) so as to not require time-critical CORBA communication over the local area network. Precise triggering of 1,600 channels of fast diagnostics and laser controls is handled during the 2-second shot interval by the distributed timing system, which is capable of providing triggers to 30-ps accuracy and stability anywhere in NIF. Hardware for the timing system was successfully developed and manufactured to specification for NIF by two vendors. Due to the zone topology used, nearly 30% of the NIF timing system is operational to this point.

Front-end processors implement distributed control points of ICCS. FEP software performs sequencing, data acquisition and reduction, instrumentation control, and input/output operations. The software framework includes a standard way for FEPs to be integrated into the supervisory system by providing the common distribution mechanism coupled with software patterns for hardware configuration, status and control (Figure 3).

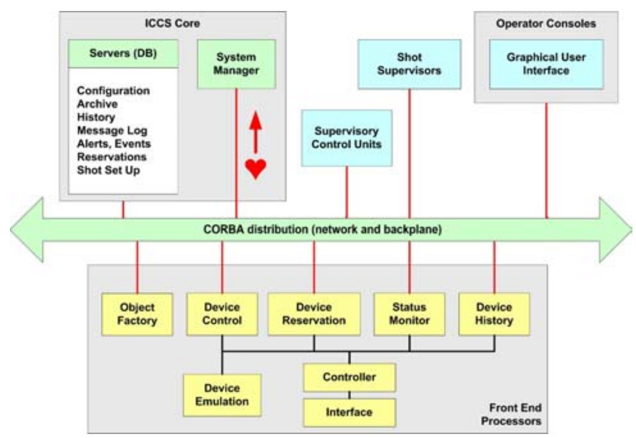

Figure 3: ICCS CORBA Distributed Framework.

ICCS is partitioned into subsystems to minimize complexity and enhance performance. There are ten subsystems that conduct NIF shots in collaboration with 17 kinds of front-end processor. The subsystems partition the control system into vertical slices consisting of a supervisor and associated FEPs that are loosely coupled to other slices.

The Beam Control Supervisor provides coordination and supervision of laser wavefront correction and laser component manual and automatic alignment and optics inspection. The Laser Diagnostics Supervisor provides functions for diagnosing laser performance by collecting integrated, transient and image information from sensors monitoring the beams. The Timing Supervisor provides monitoring of the integrated timing system. The Optical Pulse Generation Supervisor provides temporally and spatially formatted optical pulses with the energetics and optical characteristics required for injection into the laser amplifier chain. The Power Conditioning Supervisor manages high-voltage power supplies that fire flashlamps in the laser amplifiers.

The Pockels Cell Supervisor operates the plasma-electrode Pockels cell optical switch that facilitates multi-pass amplification within the main laser amplifiers. The Target Diagnostics Supervisor coordinates the collection of data from a diverse and changing set of instruments. A final Supervisor interfaces to a computerized Laser Performance Operations Model (LPOM), which is being developed to guide setup of laser operating parameters. The laser performance operations model has been used to set up every shot conducted on NIF, and produced output pulses that match those requested within a few percent [5]. The ability to meet requested energy and power goals while achieving beam-to-beam energy balance with great accuracy is unparalleled for any large, multi-beam laser fusion system. All Supervisors are controlled by a Shot Director, which is responsible for conducting the shot plan, distributing the countdown clock, and coordinating the other subsystems.

B. Computer System and Network

An Ethernet computer network will interconnect approximately 750 systems including embedded controllers, front-end processors, supervisory workstations and centralized servers. Forty-three of the 312 planned FEPs are currently installed. The CORBA software infrastructure provides location-independent communication services over TCP/IP between the application processes in the workstations, servers and FEPs. Video images sampled at up to 10 Hz frame rates from any of 500 sensor cameras are viewed by Java display GUIs at any operator console.

C. Industrial Controls

The front-end layer is divided into another segment comprised of an additional 14,000 control points that are controlled by Allen-Bradley PLCs attached to field devices such as vacuum systems for the target chamber and spatial filters, argon gas fill for beam tubes, and synthetic air for amplifier cooling. The project performed this work by contracting the subsystems as stand-alone control systems including sufficient PLC software to operate the equipment. The contractors designed and assembled the equipment off site to meet specifications and a set of common standards. Both factory and on site acceptance tests were performed. The project team developed higher-level integrated controls using the Rockwell Automation RSView software framework tool.

A separate and fully independent segment implements the facility Safety Interlock system, which monitors doors, hatches, shutters, and oxygen sensors and protects against personnel hazards by issuing equipment permissive signals. A software safety plan was developed to assure appropriate engineering rigor. The verification group formally tested the system as it was activated, which included full regression testing whenever any part of the hardware or software was modified.

D. Frameworks

The ICCS is based on a scalable software framework that is distributed over Supervisory and FEP computers throughout the NIF facility. The framework provides templates and services at multiple levels of abstraction for the construction of software applications that distribute via CORBA. Framework services such as alerts, events, message logging, reservations, user interface consistency and status propagation are implemented as templates that are extended for each application. Application software constructed on a set of framework components assures uniform behavior spanning the front-end processors (FEP) and supervisor programs. Additional framework services are provided by centralized server programs that implement database archiving, name services and process management.

The framework concept enables the cost-effective construction of the NIF software and provides the basis for long-term maintainability and upgrades. This strategy was put in place in the earliest phases of the project. Selected design patterns, pre-built components at multiple levels of abstraction, and communication infrastructure via CORBA are encapsulated in these components to assure consistency across the entire system. The frameworks reduce the amount of coding necessary by providing components that can be extended to accommodate specific additional requirements. Engineers build upon the framework for each application in order to handle different kinds of control points, controllers, user interfaces, and functionality.

E. Software Development and Testing

The strategy used to develop the NIF Integrated Computer Control System (ICCS) calls for incremental cycles of construction and formal test to deliver an estimated total of one million lines of code. Each incremental release allocates two to six months in order to implement targeted functionality consistent with overall project priorities. Releases culminate with successful formal off-line tests conducted by an independent Controls Verification and Validation (V&V) team in the ICCS Integration and Test Facility (ITF) and hardware integration labs (Figure 4) [6].

Figure 4: Formal offline tests and training are performed in the Integration and Test Facility by the Controls V&V team.

Tests are repeated on-line to confirm integrated operation and provide operator training in NIF. Offline tests in the ITF and in hardware integration labs, and these online tests in the NIF together identify 90% of software defects before the software is delivered to Operations. Test incidents are recorded and tracked from development to successful deployment by the verification team, with hardware and software changes approved by the appropriate change control board. Test metrics are generated by the verification team and monitored by the software quality assurance manager. Test results are summarized and reported to responsible individuals and area integration managers under a work authorization and permit process that assesses risk and evaluates control system upgrade readiness.

A dedicated software configuration management team builds all software releases for delivery to the verification group and the facility. Procedures for issuing service packs to efficiently and quickly patch major releases if necessary are in place.

IV. SUMMARY

NIF has entered the first phases of its laser commissioning program and has successfully operated the first 4 beams. NIF has now demonstrated the highest energy 1ω, 2ω, and 3ω beamlines in the world [3]. All subsystems successfully fired using over 100 system shots and achieved project milestones using the control system.

Approximately three quarters of the NIF software was completed and used to commission and operate the first 4 beams of NIF. The experience of operating NIF has been extremely valuable for validating the control system design and drawing out additional requirements. Over the next several years, control system hardware proven on the first 4 beams will be replicated and installed to activate additional bundles. Control points for the new bundles will be added to the data-driven architecture by reconfiguring the database.

Completing the remaining software is a large effort that involves completing shot automation for a bundle of 8 beams and developing high-level summary status displays to integrate additional bundles as they are activated. During the coming year, a separate testing effort will determine the performance limits of the control system and assure the reliability needed to scale the control system to operate multiple bundles and eventually 192 beams. The team is currently evaluating the appropriate strategy for redeploying control system processes on multiple servers to meet performance requirements as the laser scales in size by 50-fold. This straightforward scaling flexibility was a key design goal when CORBA was chosen as the distribution mechanism for ICCS.

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